# Frequency Reuse, Cell Separation, and Capacity Analysis of VHF Digital Link Mode 3 TDMA

Mohammed A. Shamma, Analex Co.

Thanh C. Nguyen, Analex Co.

Rafael Apaza, FAA

# Project

- The work here was done as part of the Advanced Communications for **Air Traffic Management Project at NASA Glenn Research Center in Cleveland, Ohio**

# Objective

- Investigate the three parameters below for VDL mode 3 type of a network
  - Frequency reuse
  - Cell Separation of co-channel cells
  - Capacity of cells
- Use FAA traffic data to get cell capacity
- Use FAA VDL 3 performance tests parameters.

# VDL 3

- Proposed by FAA to ICAO in May 1994
- VDL Mode 3 provides both data & digital voice services
- 4 logical channels in 25 kHz frequency assignment
- Each logical channel can be allocated to voice or data
- Based on D8PSK modulation at 31.5 kbps (same as VDL Mode 2)
- Access methods: TDMA
- System applies “user groups”.
  - a group of ground & airborne users
  - a controller and its controlled aircraft
- 7 configurations defined in ICAO VDL Mode 3 SARPs (See next slide)

# VDL 3 continued

| | System Configuration | User Groups Supported/Identifying Time Slots | Services to Each Group | V/D Slots Assigned to Each Group |
|---|---|---|---|---|
| Normal Range | 4V | 4/(A, B, C, D) | Dedicated voice | A, B, C, or D |
| | 3V1D | 3/(A, B, C) | Dedicated voice w/shared data | A/D, B/D, or C/D |
| | 2V2D | 2/(A, B) | Dedicated voice w/dedicated data | A/C or B/D |
| | 3T | 1/(A) | Demand assigned voice and data | B/C/D |
| Long Range | 3V | 3/(A, B, C) | Dedicated voice | A, B, or C |
| | 3S | 1/(A, B, C) | Dedicated voice circuit w/3 station diversity | A/B/C |
| | 2V1D | 2/(A, B) | Dedicated voice w/shared data | A/C or B/C |

# FAA VHF Frequency Channel Allocations

| Frequency Band | Service type | Number of Channels |
|---|---|---|
| 118.000-121.400 | ATC # | 130 |
| 121.425-121.475 | Band Protection for 121.5 | 3 |
| 121.5 | Emergency Search and Rescue | 1 |
| 121.525-121.575 | Band Protection for 121.5 | 3 |
| 121.600-121.925 | Airport Utility | 13 |
| 121.775 | SAR ELT Location Training | 1 |
| 121.95 | Aviation Support | 1 |
| 121.975 | FSS Private Aircraft Advisory | 1 |
| 122.000-122.050 | EFAS | 3 |
| 122.075-122.675 | FSS Private Aircraft Advisory | 25 |
| 122.700-122.725 | UNICOM-Uncontrolled Airports | 2 |

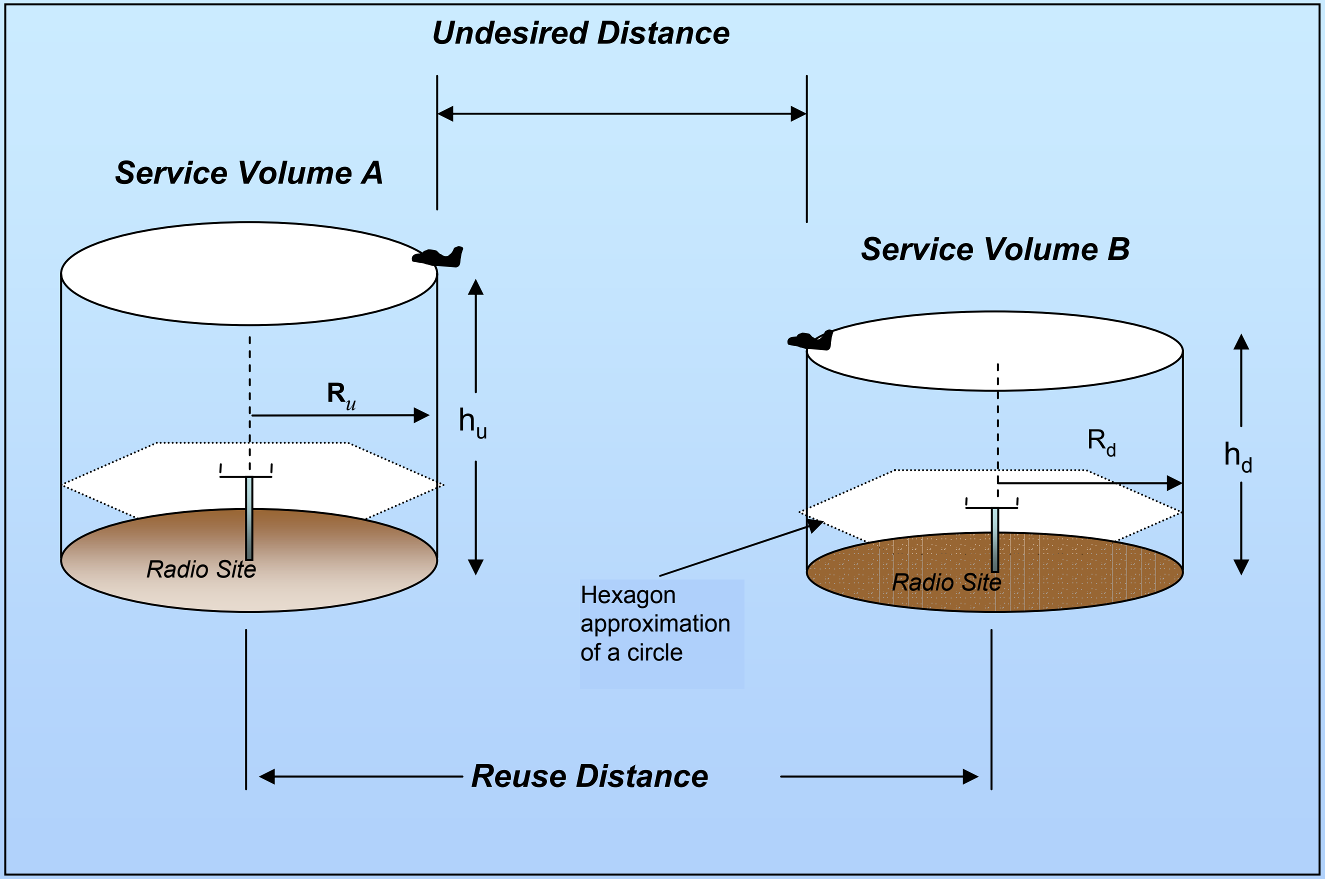
# FAA VHF Frequency Channel Allocations (continued)

| | | |
|---|---|---|
| 122.75 | Fixed Wing Aircraft | 1 |
| 122.775 | Aviation Support | 1 |
| 122.8 | UNICOM-Uncontrolled Airports | 1 |
| 122.825 | Domestic VHF | 1 |
| 122.85 | MULTICOM | 1 |
| 122.875 | UNICOM-Domestic VHF | 1 |
| 122.9 | MULTICOM SAR training | 1 |
| 122.925 | MULTICOM Special Use | 1 |
| 122.95 | UNICOM full time ATCT,FSS | 1 |
| 122.975-123.000 | UNICOM-Uncontrolled Airports | 2 |
| 123.025 | Helicopter Air to Air | 1 |
| 123.050-123.075 | UNICOM-Uncontrolled Airports | 2 |
| 123.1 | SAR;Temp.ATCT's and fly-ins with SAR coordination | 1 |
| 123.125-123.275 | Flight Test | 7 |
| 123.3 | Aviation Support | 1 |
| 123.325-123.475 | Flight Test | 7 |
| 123.5 | Aviation Support | 1 |
| 123.525-123.575 | Flight Test | 3 |
| 123.600-123.650 | FSS Air Carrier Advisory | 3 |
| 123.675-126.175 | ATC | 101 |
| 126.2 | Military Common (Advisory) | 1 |
| 126.225-128.800 | ATC | 104 |
| 128.825-132.000 | Operational Control | 128 |
| 132.025-134.075 | ATC | 83 |

# FAA VHF Frequency Channel Allocations (continued)

| | | |
|---|---|---|
| 134.1 | Military Common (Advisory) | 1 |
| 134.125-135.825 | ATC | 69 |
| 135.85 | FAA Flight Inspections | 1 |
| 135.875-135.925 | ATC | 3 |
| 135.95 | FAA Flight Inspections | 1 |
| 135.975-136.075 | ATC | 5 |
| 136.1 | Reserved for future AWOS/UNICOM | 1 |
| 136.125-136.175 | ATC | 3 |
| 136.2 | Reserved for Future AWOS/UNICOM | 1 |
| 136.225-136.250 | ATC | 2 |
| 136.275 | Reserved for future AWOS/UNICOM | 1 |
| 136.30-136.350 | ATC | 3 |
| 136.375 | Reserved for Future AWOS/UNICOM | 1 |
| 136.4-136.450 | ATC | 3 |
| 136.475 | Reserved for Future AWOS/UNICOM | 1 |
| 136.500-136.875 | Domestic VHF | 16 |
| 136.900-136.975 | International and Domestic VHF | 4 |
| | | |
| #119.675,120.625 | ATIS | 2 |
| #118.325,118.375,118.525,119.025,119.275 | AWOS/ASOS | 5 |

# Co Channel Interference, and Radio Line of Sight, Frequency Protected Service Volumes



# Radio Line of Sight

- Radio line of sight of one aircraft

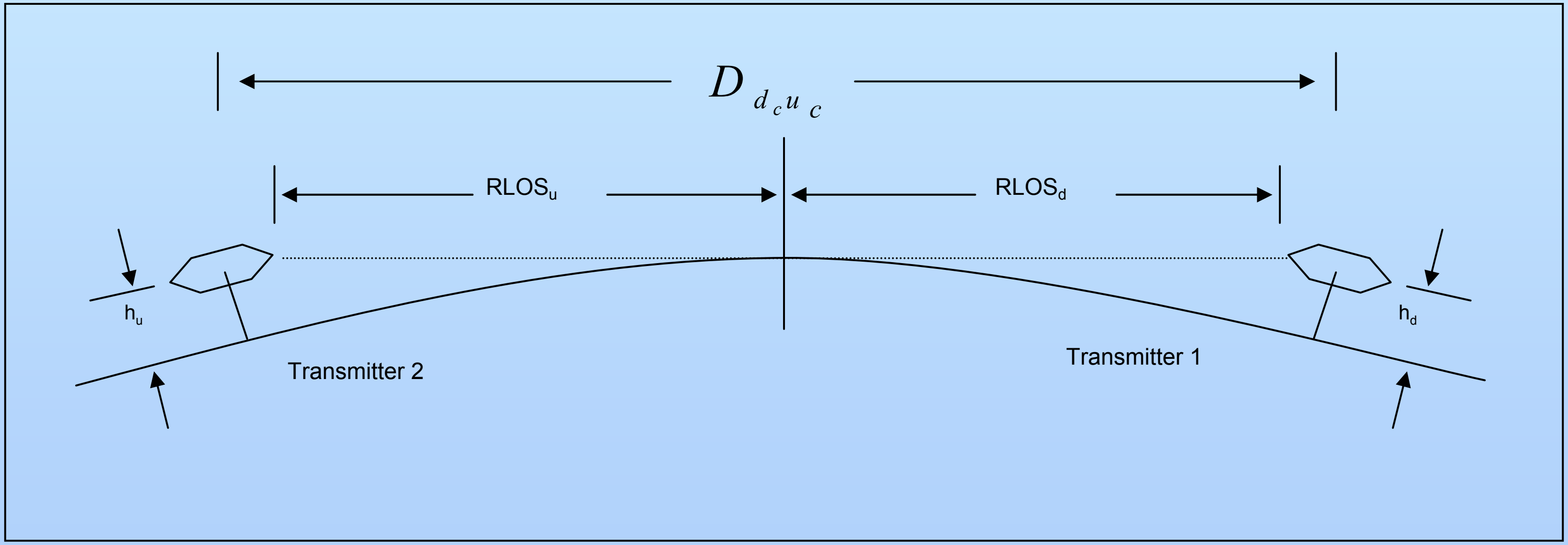
$$RLOS_d(nmi) = 1.23\sqrt{h_d}$$

- Radio line of sight between two aircrafts, and minimum distance required between the two so that not to see each other

$$D_{du} \geq 1.23(\sqrt{h_d} + \sqrt{h_u})$$

# Cell Separation based on RLOS

- Min cell center Distance for two co-channel cell to not have aircrafts be in line of sight of each other: $D_{d_c u_c} = 1.23 * (\sqrt{h_d} + \sqrt{h_u}) + R_d + R_u$



# Frequency Reuse in terms of RLOS

- The frequency reuse factor is related to the RLOS formulas and cell distances via use of: (Assumes same heights, and cell radius of two co channel cells, i.e. same type of FPSV). Also assume aircrafts at closest two points to each other)

$$f_{ru} \geq \frac{4((1.23\sqrt{h} / R) + 1)^2}{3}$$

- Above is required Frequency reuse factor such that aircrafts within co-channels do not be in line of sight of each other.

# Frequency Reuse in terms of Signal to Interference Ratio limit

- It may be possible to bring the two aircrafts within line of sight of each other as long as the S/I is met (S signal of one co channel, and I is signal of the desired cell). Assuming similar power setting from the two aircrafts (10 to 20 Watts) we have:

$$f_{ru} = \begin{cases} \frac{1}{3}\left[(\sqrt{6})10^{10\log(S_d/I_{total\_interf})_{required}/20} + 2\right]^2 \\ \frac{1}{3}\left[(10^{10\log(S_d/I_u)_{required}/20} + 2\right]^2 \end{cases}$$

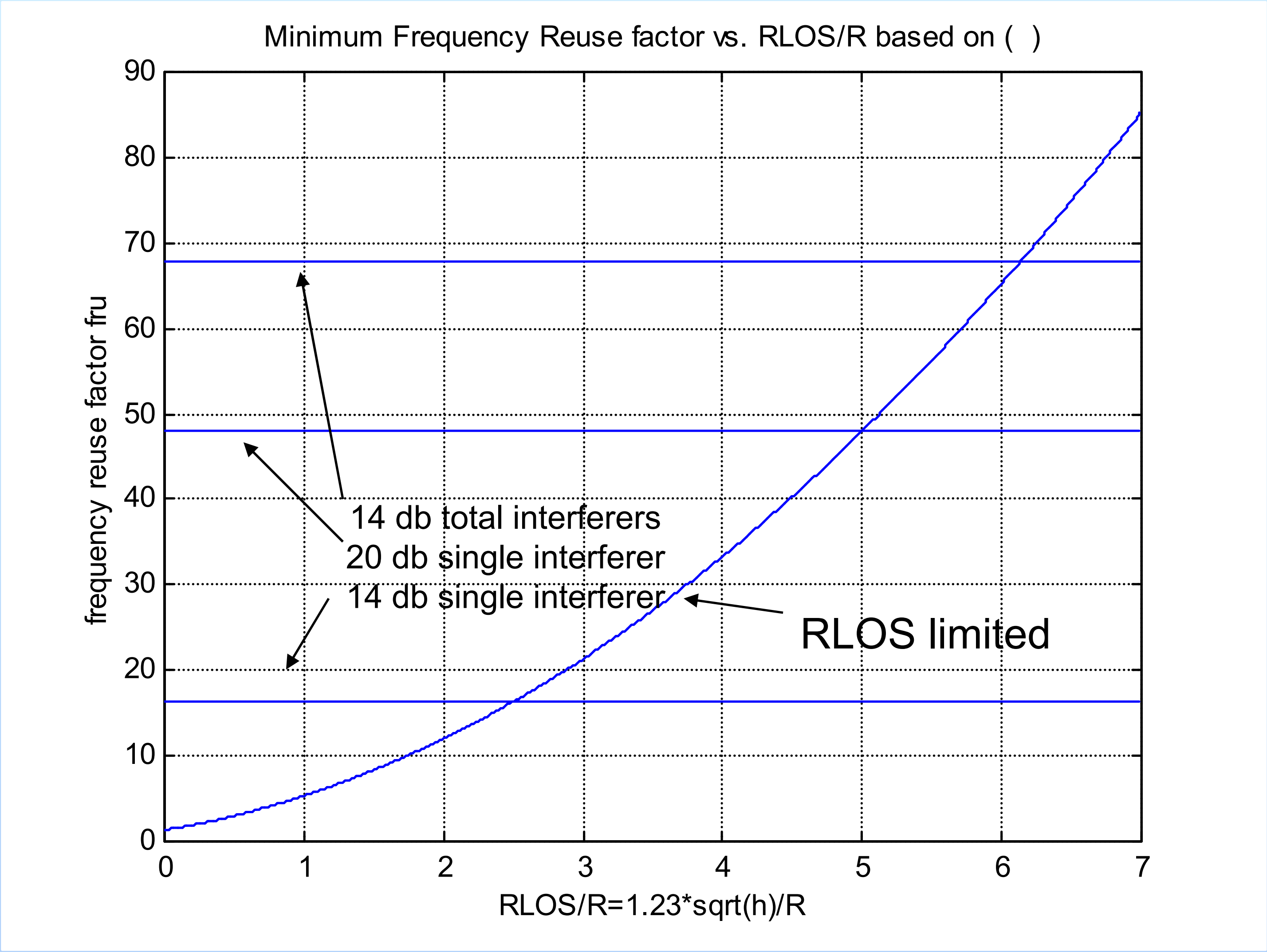
For total interference from 6 sources MITRE approach

For one interference source

# FAA S/I for Co-Channel Interference

| Required Signal to co channel Interference Ratio (total or single) | Minimum frequency reuse factor required based on equation () first part for Total Interference assumption | Minimum frequency reuse factor required based on equation () second part for Single Interferer assumption |
|---|---|---|
| 14 db min (analog system []) | 67.9 (plotted in Figure 3) | 16.4 9 (plotted in Figure 3) |
| 20 db FAA tested VDL3 [] | 234 | 48.9 (plotted in Figure 3) |
| 26 db a maximum specified [] | 862.7 | 160.6 |

# Frequency reuse based on RLOS and S/I



# RLOS and R for different FPSV

| Service Type | Altitudes h (ft) | Service Radius R (nmi) | RLOS (nmi) from formula (2) | RLOS/R |
|---|---|---|---|---|
| Super High Altitude En Route (SE) | >45000 | 150 | >260.9 | >1.74 |
| High Altitude En Route | 45000 | 150 | 260.9 | 1.74 |
| Intermediate Altitude En Route (IE) | 25000 | 60 | 194.5 | 3.24 |
| Low Altitude En Route (LE) | 18000 | 60 | 165 | 2.75 |
| Approach Control (AC), Departure Control (DC), Arrival Automated Terminal Information Service (ATIS) | 25000 | 60 | 194.5 | 3.24 |
| Local Control (LC) | 25000 | 30 | 194.48 | 6.5 |
| Weather (AWOS/ASOS) | 10000 | 25 | 123 | 4.92 |
| Ground Control (GC), Clearance Delivery (CD), Departure ATIS | 100 | 2-5 | 12.3 | 6.15-2.46 |

# Frequency reuse factor for different FSPV

| **Service Type** | **RLOS/ R** | $f_{ru}$ from minimum value shown on Plot in Figure 3 with **14 db** signal to Interference ratio (**single Interferer**) | $f_{ru}$ from minimum value shown on Plot in Figure 3 with **14 db** signal to Interference ratio **total Interferers**) | $f_{ru}$ from minimum value shown on Plot in Figure 3 with **20 db** signal to Interference ratio (**single Interferer**) | $f_{ru}$ from minimum value shown on Plot in Figure 3 with **20 db** signal to Interference ratio (**total Interferers**) |
|---|---|---|---|---|---|
| Super High Altitude En Route (SE) | >1.74 | >10 | >10 | >10 | >10 |
| High Altitude En Route | 1.74 | 10 | 10 | 10 | 10 |
| Intermediate Altitude En Route (IE) | 3.24 | 16.49 (interference limited) | 23.98 | 23.98 | 23.98 |
| Low Altitude En Route (LE) | 2.75 | 16.49 (interference limited) | 18.76 | 18.76 | 18.76 |
| Approach Control (AC), Departure Control (DC), Arrival Automated Terminal Information Service (ATIS) | 3.24 | 16.49 (interference limited) | 23.98 | 23.98 | 23.98 |
| Local Control (LC) | 6.5 | 16.49 (interference limited) | 67.9 (interference limited) | 48.9 (interference limited) | 75 |
| Weather (AWOS/ASOS) | 4.92 | 16.49 (interference limited | 46.74 | 46.74 | 46.74 |
| Ground Control (GC), Clearance Delivery (CD), Departure ATIS | 6.15-2.46 | 16.49 (interference limited)-15.97 | 67.9 (interference limited)-15.97 | 48.9 (interference limited)-15.97 | 68.18-15.97 |

# Cell Capacity formulation

- Cell Capacity in terms of:
  - Number of TDMA slots (used 3 for max data)
  - Total Bandwidth available / channel bandwidth =Number of channels (used 524, common ATC value used in literature. Note 527 based on total from VHF manual)
  - Frequency Reuse from results in Tables (Min)

$$Cell\_Capacity = \frac{BW_{total} N_{slots}}{BW_{channel} f_{RU}}$$

# Cell separation and Max Cell capacity for different FSPV

| Service Type | **Required Separation (nmi) to a similar cell**, using frequency reuse factors **of 14 db single interferer** (Table 4) and formula (6) $D_{d_c u_c} = R\sqrt{3 f_{RU}}$ | **Single Cell Capacity** using frequency reuse factors of **14 db single interferer** (Table 4) and formula (1) $Cell\_Capacity = \frac{BW_{total} N_{slots}}{BW_{channel} f_{RU}}$ with $N_{slots}$=3 and $BW_{total}/BW_{channel}$= 524 with all 100 % distribution to each FPSV | **Required Separation (nmi) to a similar cell**, using frequency reuse factors **of 20 db total interferers** (Table 4) and formula (6) $D_{d_c u_c} = R\sqrt{3 f_{RU}}$ | **Single Cell Capacity** using frequency reuse factors of **20 db total interferers** (Table 4) and formula (1) $Cell\_Capacity = \frac{BW_{total} N_{slots}}{BW_{channel} f_{RU}}$ with $N_{slots}$=3 and $BW_{total}/BW_{channel}$= 524 with all 100 % distribution to each FPSV |
|---|---|---|---|---|
| Super High Altitude En Route (SE) | >821.58 | <157 | >821.58 | <157 |
| High Altitude En Route | 821.58 | 157 | 821.58 | 157 |
| Intermediate Altitude En Route (IE) | 422.01 | 95 | 508.90 | 65 |
| Low Altitude En Route (LE) | 422.01 | 95 | 450 | 83 |
| Approach Control (AC), Departure Control (DC), Arrival Automated Terminal Information Service (ATIS) | 422.01 | 95 | 508.90 | 65 |
| Local Control (LC) | 211.00 | 95 | 450 | 20 |
| Weather (AWOS/ASOS) | 175.84 | 95 | 296.04 | 33 |
| Ground Control (GC), Clearance Delivery (CD), Departure ATIS | 14.07-34.61 | 95-98 | 28.60-34.61 | 23-98 |

# Detroit (DTW) Example

- Collected information from:
  - ASR-9 Terminal Radar System (60nmi coverage)
  - Enhanced Traffic Management System (ETMS), gathers long range radar target information for display.
- Traffic Samples:
  - Terminal Area: Evaluated traffic in DTW Approach and Local Control
  - En-route Area: Evaluated One sector in SE, HE, IE, LE in the South East of Michigan.
- Results: Number of channels available per cell for each FPSV, and for the entire CONUS for 14 db single and 20 db total interferer signal to interference ratio.
  - SE for the 14 db and 20 db cases are the same (6 channels per cell, and 190 channels for CONUS), slightly more than the number of aircrafts flying at that sector.
  - HE with 29 channels per cell, and 918 for CONUS, slightly larger than the number of aircrafts at that sector.
  - IE shows 9 and 6 channels per cell for the 14 and 20 db cases respectively (with 1782 and 1188 for CONUS). Slightly less than number of flying aircraft.
  - LE, AC, DC, and LC, have slightly less channels than aircrafts with the expected worst case being the 20 db (due to stricter requirement on interference levels).

| Heights Range (ft) | Number of aircraft | Percentage from total |
|---|---|---|
| > 35000 | 4 | 3.96 % |
| 24000 – 35000 | 17 | 16.83 % |
| 10000 – 24000 | 10 | 9.90 % |
| 640 – 10000 | 47 | 46.53 % |
| Approach Control | 16 | 15.84 % |
| Local Control | 7 | 6.93 % |

| **Service Type** | Number of service volume that fits in CONUS. $= \frac{CONUS\_area}{\pi R^2}$ (using nmi $^2$ for CONUS area) | **Available number of ch annels, Single Cell Capacity** using frequency reuse factors of **14 db single interferer** (Table 1) and formula (1) $Cell\_Capacity = \frac{BW_{total} N_{slots}}{BW_{channel} f_{RU}}$ with $N_{slots}$=3 and $BW_{total}/BW_{channel}$ = 524 with Table 6 distribution to each FPSV | **Available number of channels for all C ONUS** using percentages obtained in table 6 using single cell capacity frequency for 14db. | | **Available number of channels, Single Cell Capacity** using frequency reuse factors of **20 db total interferers** (Table 1) and formula (1) $Cell\_Capacity = \frac{BW_{total} N_{slots}}{BW_{channel} f_{RU}}$ with $N_{slots}$=3 and $BW_{total}/BW_{channel}$ = 524 with Table 6 distribution to each FPSV | **Available number of channels for all CONUS** using percentag es obtained in table 6 using single cell capacity frequency for 20 db. |
|---|---|---|---|---|---|---|
| Super High Altitude En Route (SE) | 31.68 | 6 | 190 | | 6 | 190 |
| High Altitude En Route (HE) | 31.68 | 29 | 918 | | 29 | 918 |
| Intermediate Altitude En Route (IE) | 198 | 9 | 1782 | | 6 | 1188 |
| Low Altitude En Route (LE) | 198 | 44 | 8712 | | 39 | 7722 |
| Approach Control (AC), Departure Control (DC), | 198 | 15 | 2970 | | 10 | 1980 |
| Local Control (LC) | 792 | 7 | 5544 | | 1 | 792 |

# Conclusions

- Analyses done to compute frequency reuse, cell separation and cell capacity for different FAA FPSV
- Use of RLOS and S/I of co-channel utilized
- Use of different S/I limits based on FAA data
- Capacity shows sufficient for future traffic, assuming some sharing of channels
- Capacity based on a traffic distribution example shows more realistic limits

# Future Recommendations

- Use simulations to back up findings based on various scenarios
- Recommend limits on S/I based on results
- Investigate new frequency planning approaches if possible
- Show where draw backs in current frequency plan exist.
- Incorporate other factors such as adjacent channel interferences
- Use current results to compare to actual system capacities and recommend improvements.